

Response to Reviewers

Title: Improving multi-objective reservoir operation optimization with sensitivity-informed problem decomposition

Manuscript ID: hess-2015-92

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Dear Reviewers:

We greatly appreciate you for your valuable comments and suggestions. The comments are all valuable and very helpful for revising and improving our paper. The responses to the comments are listed below.

Reviewer #1

Comment 1: Lines 17-24 on page 3723: Does the red line with circle in Figure 1 represent water supply rule curve for agriculture itself or total water supply of agriculture and industry? If it is for agriculture itself, “The agricultural demand D1 could be fully supplied when the actual water storage is in zone 1, which is above the water supply rule curve for agriculture,” - does it mean agriculture has the higher priority than industry water use? However, “... the industrial demand D2 has to be rationed when the actual water storage is in zone 3, which is below the water supply rule curve for industry.” I think that both D1 and D2 may need to be rationed when the water storage is in zone 2. Do I miss something? Please clarify the explanation for Figure 1.

Response:

As we know that water demand could be fully satisfied only when there is sufficient water in reservoir. Water supply operation rule curve, which is used to operate most reservoirs in China, represents the limited storage volume for water supply in each

period of the operating year. In detail, water demand will be fully satisfied when the reservoir storage volume is higher than water supply operation rule curve, whereas water demands need to be rationed when the reservoir storage volume is lower than water supply operation rule curve. In general, a reservoir has more than one water supply target, and there is one to one correspondence between water supply rule curve and water supply target. The water supply with lower priority will be limited prior to the water supply with higher priority when the reservoir storage volume is lower. To reflect the phenomenon that different water demands can have different reliability requirements and different levels of priority in practice, the operation rule curve for the water supply with the lower priority is located above the operation rule curve for the water supply with the higher priority.

Therefore, in Fig. 1, the red line with circle represent water supply rule curve for agriculture, the green line with triangle represent water supply rule curve for industry, and the water supply rule curve for agriculture with lower priority is located above the water supply rule curve for industry with higher priority. Specifically, both the agricultural demand D1 and the industrial demand D2 could be fully supplied when the actual water storage is in zone 1, which is above the water supply rule curve for agriculture; when the actual water storage is in zone 2, which is above the water supply rule curve for industry and below the water supply rule curve for agriculture, the industrial demand D2 could be fully supplied, and the agricultural demand D1 has to be rationed; both the agricultural demand D1 and the industrial demand D2 have to be rationed when the actual water storage is in zone 3, which is below the water supply rule curve for industry.

We have clarified the explanation for Fig. 1 in the revised manuscript.

Comment 2: Does the annual value of R in equation (2) equal to $W_{1,j}+W_{2,j}$?

Response:

In Equation (2), R_t is delivery for water use during the period t . Because $W_{i,j}(x)$ is the sum of delivered water for water demand i during the j th year, the sum value of

R during the j th year equals to $W_{1,j}(x) + W_{2,j}(x)$ in this paper.

We have added the relative description in the revised manuscript.

Comment 3: Line 10 on page 3727: “need to be translated”

Response:

I have corrected the sentence to “The additive ε -indicator measures the smallest distance that a solution set needs to be translated to completely dominate the reference set”.

We have revised the sentence in the revised manuscript.

Comment 4: Lines 20-22: 39 decision variables for one year? Equation (1) shows there are more than 1 year.

Response:

Water supply operation rule curves represent the limited storage volume for water supply in each period of the operating year, which is divided into 24 time periods (with ten days as scheduling horizon from April to September, and a month as scheduling horizon in the remaining months). Decision variables are storage volumes at different time periods on the operation rule curves. For the industrial curve, there are twenty-four decision variables. Because the agricultural water supply occurs only in the periods from the second ten-day of April to the first ten-day of September, there are fifteen decision variables for the agricultural curve. Therefore, there are thirty-nine decision variables in total.

Because it could be assumed that the historical inflow into the reservoir would be repeated in the future, to provide long-term operation guidelines for reservoir management to meet expected water demands in a future planning year, the water demands in the future planning year and long-term historical inflow are used. The optimization objectives for water supply operation rule curves are to minimize water shortages during the long-term historical period. Therefore, Equation (1) computes the

water shortages in all historical years.

We have added the relative description in the revised manuscript.

Comment 5: Figure 4: Please explain why those decision variables are most sensitive, intuitively or conceptually. Same for Figure 8.

Response:

The most sensitive decision variables could be identified by imposing a user specified threshold (or classification) of sensitivity.

The thresholds used to differentiate sensitive and insensitive decision variables are based only on the magnitudes of the sensitivity total-order indices for each decision variable. The thresholds were determined by plotting the magnitudes of the sensitivity total-order indices for each decision. Results were classified as sensitive where the sensitivity total-order index values are larger and changed the most significantly. Insensitive parameters had small sensitivity total-order index values that could not be distinguished. These thresholds are subjective and their ease-of-satisfaction decreases with increasing numbers of parameters or parameter interactions. In all of the results for the Sobol's method, parameters classified as the most sensitive contribute, on average, at least 10 percent of the overall model variance (Tang et al., 2007a, b).

Therefore, in this paper, the most sensitive decision variables are identified based on a total-order Sobol's index threshold of greater than 10% and 3% in Fig. 4 (39 decision variables) and Fig. 8 (126 decision variables) respectively.

We have added the relative description in the revised manuscript.

Comment 6: Lines 4-7 on page 3734: "...the Pareto optimal solutions were then used as starting points to start a complete new search..." Since the Pareto optimal solutions from the simplified problem only include the sensitive decision variables, how are the initial values of insensitive variables for the full search determined?

Response:

In this paper, the simplified problem is solved with the optimization of sensitive decision variables, the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem. Therefore, the solutions from the simplified problem, which include optimal sensitive decision variables and the constant insensitive decision variables, are used as starting points to start a complete new search.

We have added the relative description in the revised manuscript.

Comment 7: Lines 6-21 on page 3735: From Figure 10, the authors conclude that the preconditioned full search is more reliable than the regular full search. Did you try different settings for the pre-conditioned full search? E.g., random seeds for obtaining the pre-conditioning search or other parameter settings.

Response:

In this paper, we have tried ten random seed trials for obtaining the pre-conditioning search and full search respectively, and we conclude that the preconditioned full search is more reliable than the regular full search based on the comparison of solutions obtained through ten random seed trials.

References

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Reviewer #2

Comment 1: The term ‘problem decomposition’ introduced in the title of the article and throughout the text is somewhat misleading. This term commonly refers to approaches when a complex problem is ‘decomposed’ in a number of simpler problems that can be solved in an easier manner. The approach in this article is different because here the same optimization problem is being solved, just with reduced number of decision variables. My suggestion is to change this term both in the title and throughout the text into something like: “Improving.....with sensitivity-informed reduction of problem size” (for the title).

Response:

We agree with the reviewer that the term “dimension reduction” is better for the paper. We have changed the term “problem decomposition” into the term “dimension reduction” throughout the revised manuscript including the title.

Comment 2: Section 1 ‘Introduction’ does not present any reference to addressing optimization of ROS by algorithms that seek the optimal reservoir operation policy as trajectories through time (e.g. Dynamic Programming, Stochastic Dynamic Programming and more recently Reinforcement learning and others). This is not the approach taken in the current article where MOEA algorithms are used that treat the rule curve values in time as individual decision variables (parameters). However some recognition of the existence of the other methods mentioned above is needed in the introduction. There are sufficient references in HESS as well as in numerous other journals regarding these approaches.

Response:

We agree with the reviewer, and have added the description of relevant algorithms

that seek the optimal reservoir operation policy as trajectories through time (e.g. Dynamic Programming, Stochastic Dynamic Programming and more recently Reinforcement learning and others) as follows.

“In order to solve the ROS problem, there are different approaches, such as implicit stochastic optimization (ISO), explicit stochastic optimization (ESO), and parameter-simulation-optimization (PSO) (Celeste and Billib, 2009). ISO uses deterministic optimization, e.g., dynamic programming, to determine a set of optimal releases based on the current reservoir storage and equally likely inflow scenarios (Young, 1967; Karamouz and Houck, 1982; Castelletti et al., 2012; François et al., 2014). Instead the use of equally likely inflow scenarios, ESO incorporates inflow probability directly into the optimization process, including stochastic dynamic programming and Bayesian methods (Huang et al., 1991; Tejada-Guibert et al., 1995; Powell, 2007; Goor et al., 2010; Xu et al., 2014). However, many challenges remain in application of these two approaches due to their complexity and ability to conflicting objectives (Yeh, 1985; Simonovic, 1992; Wurbs, 1993; Teegavarapu and Simonovic, 2001; Labadie, 2004).

In a different way, PSO predefines a rule curve shape and then utilizes optimization algorithms to obtain the combination of rule curve parameters that provides the best reservoir operating performance under possible inflow scenarios or a long inflow series (Nalbantis and Koutsoyiannis, 1997; Oliveira and Loucks, 1997). In this way, most stochastic aspects of the problem, including spatial and temporal correlations of unregulated inflows, are implicitly included, and reservoir rule curves could be derived directly with genetic algorithms and other direct search methods (Koutsoyiannis and Economou, 2003; Labadie, 2004). Because PSO reduces the curse of dimensionality problem in ISO and ESO, it is widely used in reservoir operation optimization (Chen, 2003; Chang et al., 2005; Momtahan and Dariane, 2007). In this study, the PSO-based approach is used to solve the ROS problem.”

Comment 3: Some clarifications are needed regarding Equation (1) on page 3725 that introduces the general formulation of the objective functions.

Specifically, the term $W_{i,j}(x)$, which represents the sum of delivered water for water demand i in year j , needs to be clarified. My understanding is that during one optimization trial the rule curve values for the selected periods in one year are set and then the system is simulated for 40 years (1956-2006) using predicted demands of 2030. This simulation results in storage volumes that are sometimes below the rule curves, which are resulting in water shortages calculated as demand – actually delivered water. The question is the following: Is the water actually delivered in these periods calculated with the reduction factors (α_1 and α_2) discussed in the paragraph just above Equation (1) or not? If these are used – please elaborate how these reduction factors are introduced (are they constant or dependent on how far below is the actual reservoir storage volume below the rule curve(s)?).

Response:

Firstly, water supply operation rule curves represent the limited storage volume for water supply in each period of an operating year, which is divided into 24 time periods (with ten days as scheduling time step from April to September, and one month as scheduling time step in the remaining months). Decision variables are storage volumes at different time periods on the operation rule curves. To provide long-term operation guidelines for reservoir management to meet expected water demands for future planning years, the projected water demands and long-term historical inflow are used. The optimization objective for water supply operation rule curves is to minimize water shortages during the long-term historical period. Therefore, Equation (1) computes the water shortages in all historical years. The explanations of symbols have been updated in the revised manuscript.

Secondly, during the long-term simulation, when actual water storage is below the water supply rule curve, the water demand has to be rationed, i.e., applying the rationing factor. In general, a reservoir has more than one water supply targets, and the different water demands can have different reliability requirements and thus different levels of priority in practice. During drought, water demand with lower

priority should be rationed first, the reduction degree ought to be larger and water-supply reliability ought to be smaller. Therefore, the operation rule curve for the water supply with the lower priority and larger reduction degree is located above the operation rule curve for the water supply with the higher priority and smaller reduction degree. In this paper, Fig. 1 shows water supply operation rule curves for agriculture and industry, where α_1 and α_2 are the reducing factors for industrial water demand and agricultural water demand, respectively.

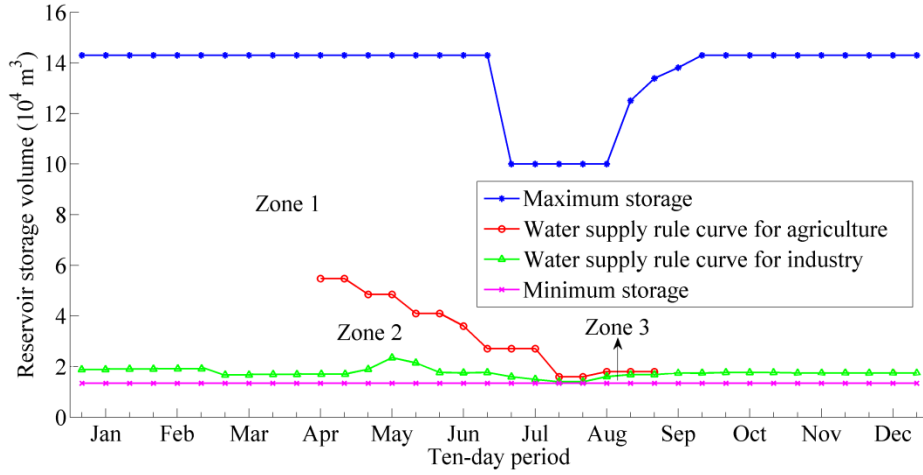


Fig. 1 Reservoir operational rule curves

Thirdly, the rationing factors used to determine the amount of water supply for different water demands can be either assigned according to the experts' knowledge or determined by optimization (Shih and ReVelle, 1995). In this paper, rationing factors are given at the reservoir's design stage according to the tolerable elastic range of each water user in which the damage caused by rationing water supply is limited. As mentioned above, rule curves for different water demands have different rationing factors, which remain constant and are not dependent on how far below is the actual reservoir storage volume below the rule curve during the long-term simulation. That is, as long as actual water storage is below the water supply rule curve, the water demand has to be rationed. Specifically, in Equation (1), the term $W_{i,j}(x)$ is the actually delivered water for water demand i during the j th year, and is calculated below using agricultural water demand ($i = 1$) as an example. If the actual water storage is above the water supply rule curve for agricultural water demand ($i = 1$) at period t in a year, the delivered water at period t is its full demand without being

rationed, $D_{1,t}$. If the actual water storage is below the water supply rule curve for agricultural water demand at period t , the delivered water for agricultural water demand at period t is its rationed demands, $\alpha_1 * D_{1,t}$.

We have added the relevant clarifications in the revised manuscript.

Comment 4: Please provide some clarification regarding Figure 1. Is this just an example of rule curves for a reservoir (as suggested in the figure caption), or these are actual (currently used?) rule curves for Dahuofang reservoir (as suggested in the text on page 3723, lines 9-10)?

Response:

Fig. 1 is just an illustration of rule curves for Dahuofang reservoir based on the projected water demands and long-term historical inflow, and they are not actual (current used) rule curves. The currently used rule curves are in a similar shape but are based on the current water demands. This has been made clear in the revised manuscript.

Comment 5: If the rule curves in Figure 1 are actual for Dahuofang reservoir, the periods when there seem to be conflicting objectives (flood protection, agricultural water supply and industrial water supply) are limited (April-October). Industrial water supply curve is very close to minimum storage throughout the year and agriculture water supply curve is considered only in the period April-October. The sensitivity-related results presented in Figure 4 are then not really clear. For example, how can the high sensitivity for industrial water supply curve in periods 1,2,3,10,11 and 12 (presumably January-March and October-December) be explained? Is this related to the interactive effects, only briefly mentioned in lines 22-24 on page 3730? The authors are kindly asked to provide clarifications / explanations regarding the sensitivity-related results presented in Figure 4.

Response:

As mentioned above, Fig. 1 is just an illustration of rule curves for Dahuofang reservoir based on the projected water demands and long-term historical inflow, and they are not actual (current used) rule curves.

The rule curves for Dahuofang reservoir from the final Pareto fronts based on the projected water demands and long-term historical inflow are shown in Fig. 8 (S2).

Firstly, the optimal operational rule curves in Fig. 8 (S2) have the same characteristics as they are used in practice. During the pre-flood season (from April to June), the curves gradually become lower so that they can reduce the probability of limiting water supply and empty the reservoir storage for the flood season (from July to early September). During the flood season, the curves also stay in low positions owing to the massive reservoir inflow and the requirement of flood control, so that it is beneficial to supply as much water as possible. However, during the season from mid-September to March, the curves remain high, especially from mid-September to October, in order to increase the probability of limiting water supply and retaining enough water for later periods to avoid severe water-supply shortages as drought occurs.

Secondly, Fig. 8 (S2) shows that different water demands occur at different periods, e.g., industrial water demand occurs throughout the whole year, and agricultural water demand occurs only at the periods from the second ten-day of April to the first ten-day of September. Due to the higher priority of industrial water supply than agricultural water supply, the industrial water supply curve is more close to minimum storage throughout the year than the agricultural water supply curve. Due to the conflicting relationship between industrial and agricultural water demands, the industrial water supply curve is higher during the non-flood season. Thus, if the industrial water supply curve is too low during the non-flood season from January to April, which implies that the industrial water demand is satisfied sufficiently, there would not be enough water supplied for the agricultural water demand in the same year. Similarly, if the industrial water supply curve is too low during the non-flood season from September to December, there would not be enough water supplied for

the agricultural water demand in the next one or more years.

Thirdly, the inflow and industrial water demands are relatively stable during the non-flood seasons from January to March and from October to December, so one month is taken as the scheduling time step, which is in accordance with the requirement of Dahuofang reservoir operation in practice. Due to the larger amount of industrial water demand in periods 1, 2, 3, 10, 11 and 12 (January-March and October-December) than other periods, the water storages at these time periods are very important to industrial water supply, making them the most sensitive variables. Because the agricultural water demand is very high during the non-flood period from April to May, the agricultural water supply curve at this time period is higher, and the water storages at time periods from agr4-2 to agr5-3, i.e., the water storages at the first five time periods of water supply operation rule curve for agricultural water demand, are the most important variables. On the other hand, in practice, if the agricultural water demand could not be satisfied at the first few periods of water supply operation rule curve, the agricultural water supply at each period throughout the year would be limited, i.e., the interactive effects from variables are noticeable at time periods from agr4-2 to agr5-3.

We have added the above figure and more clarifications and explanations in the revised manuscript.

Comment 6: From Figure 1 it can be noticed that the second half of the period when water from the Dahuofang reservoir is needed for agriculture (irrigation) coincides with the flood season (therefore the conflict, since the reservoir storage needs to be reduced to accommodate the flood wave). This is also confirmed in the text on page 3728 (lines 17-19), when the decision variables for the agriculture water supply curve have been selected for the period April-September. However this is somewhat counter-intuitive. Why would irrigation be needed during the flood (wet) season? Can you please clarify this?

Response:

During the flood season, there are still agricultural water demands due to temporal and spatial variations of rainfall though they are significantly reduced. Also note that the water supply curves are developed based on a historical, long-term rainfall series and the projected demands are also based on historical demands, covering stochastic uncertainties in demands and rainfalls.

We have added some clarifications in the revised manuscript.

Comment 7: It is not clear how are the rule curve values set for periods that are not varied during the optimization (not considered as decision variables) in the simplified problems that also provide initial values for the pre-conditioned optimization. Please explain this somewhere in the article.

Response:

In this paper, the simplified problem is solved with the optimization of sensitive decision variables; and the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem. Therefore, the solutions from the simplified problem, including optimal sensitive decision variables and the constant insensitive decision variables, are used as starting points for a complete new search.

We have added the relevant explanations in the revised manuscript.

Comment 8: Even though the article is largely focused on demonstrating the efficiency gains due to the introduction of the sensitivity analysis step, it will be good to show some results in terms of actual gains regarding the considered objectives after the optimization. Is there a base case (without optimization) to which optimal solutions can be compared? If yes, it will be good to show the shortages for the base case compared with few solutions from the final Pareto front(s) (e.g. one favoring industry, one favoring agriculture and one compromise solution), and to show in an additional

figure the actual optimal rule curves for such solutions (to be compared perhaps with those in Figure 1).

Response:

As mentioned above, the currently used rule curves for Dahuofang reservoir are based on the current water demands. However, this paper aims to provide long-term operation guidelines for reservoir management to meet expected water demands for future planning years based on the projected water demands and long-term historical inflow. Therefore, comparisons are made among the optimized solutions from the final Pareto fronts, including industry-favoring solution (S0), agriculture-favoring solution (S1) and compromised solution (S2). The comparisons of water shortage indices among different solutions are shown in Table 3, and the optimal rule curves for different solutions are shown in Fig. 8.

Table 3 Comparisons of water shortage indices among different solutions

Solutions	Water Shortage Index (-)	
	Industrial water demand	Agricultural water demand
(S0) Industry-favoring solution	0.000	3.550
(S1) Agriculture-favoring solution	0.020	1.380
(S2) Compromised solution	0.007	1.932

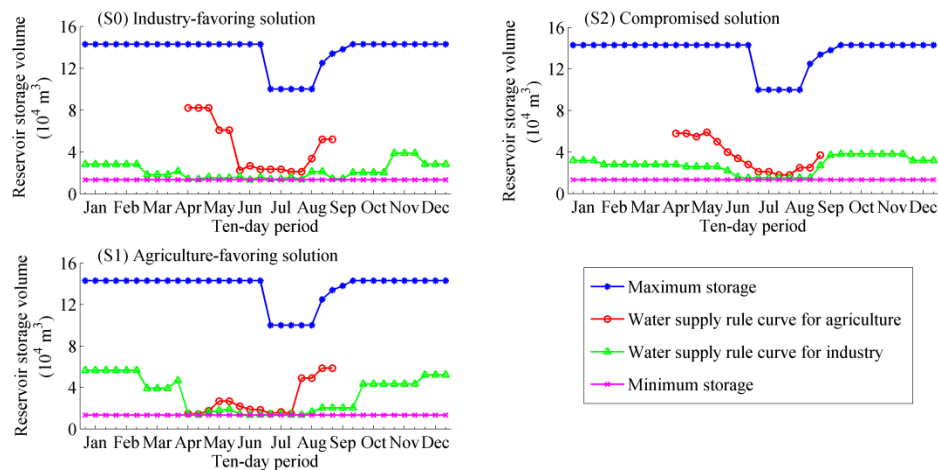


Fig. 8 Optimal rule curves for different solutions, (S0) Industry-favoring solution; (S1) Agriculture-favoring solution; (S2) Compromised solution

It could be seen from Table 3 and Fig. 8 that there are larger differences among

different solutions. With industry-favoring solution (S0), the agricultural water supply curve at the period from April to May is the highest among the three solutions. Because the agricultural water demand is very high during the non-flood period from April to May, the highest position of agricultural water supply curve at these periods could cause that the agricultural water demand would not be satisfied at the first few periods of agricultural water supply operation rule curve, and the agricultural water supply at each period throughout the year would be limited easily. Therefore, in S0, the industrial water demand could be fully satisfied through limiting agricultural water supply to a large extent, and lowering the industrial water supply curve; industrial and agricultural water shortage indices are 0.000 and 3.550, respectively. Opposite to S0, the agricultural water demand in S1 could be satisfied largely through lowering the agricultural water supply curve on the period from April to May and raising the industrial water supply curve; and industrial and agricultural water shortage indices are 0.020 and 1.380, respectively. Compared with solutions S0 and S1, two objectives are balanced in compromised solution (S2), where industrial and agricultural water shortage indices are 0.007 and 1.932, respectively.

We have added the relevant explanations in the revised manuscript.

Comment 9: It will be good if the authors can provide in section 5.3 ‘Discussions’ some thoughts regarding the expectations for similar efficiency gains in other ROS optimization problems (and other water-related optimization problems in general). In other words, how much are the large efficiency gains reported case-specific (type of problem and problem formulation, selection of initial number of decision variables, etc) compared to gains that can be expected in general.

Response:

This study investigates the effectiveness of a sensitivity-informed optimization method for the ROS multi-objective optimization problems. The method uses a global sensitivity analysis method to screen out insensitive decision variables and thus forms

simplified problems with a significantly reduced number of decision variables. The simplified problems dramatically reduce the computational demands required to attain Pareto approximate solutions, which themselves can then be used to pre-condition and solve the original (i.e., full) optimization problem.

In reality for a very large and computationally intensive problem, the full search with all the decision variables would likely be so difficult that it may not be optimized sufficiently. However, as shown here, these simplified problems can be used to generate high quality pre-conditioning solutions and thus dramatically improve the computational tractability of complex problems. The framework could be used for solving the complex optimization problems with a large number of decision variables.

For example, Fu et al. (2012) has used the framework for reducing the complexity of the multi-objective optimization problems in water distribution system (WDS), and applied it to two case studies with different levels of complexity - the New York Tunnels rehabilitation problem and the Anytown rehabilitation/redesign problem. For the New York Tunnels network, because the original optimization problem has 21 decision variables (pipes) and each variable has 16 options, the decision space is $16^{21} = 1.934 \times 10^{25}$. The simplified problem with 8 decision variables based on Sobol's analysis have a decision space of $16^8 = 4.295 \times 10^9$. To obtain the same threshold of hypervolume value 0.78 for the New York Tunnels rehabilitation problem, the most the pre-conditioned search need is 60 to 70% fewer NFE relative to the full search through 50 random seed trials. In the case of the Anytown network, the original problem has a space of 2.859×10^{73} , and the simplified problem has a significantly reduced space of 8.364×10^{38} . Through 50 random seed trials for the Anytown rehabilitation/redesign problem, the full search requires average of 800000 evaluations to reach hypervolume value 0.77, and the pre-conditioned search exceeds hypervolume value 0.8 in all trials in fewer than 200000 evaluations. The results also show that searching in such significantly reduced space formed by sensitive decision variables makes it much easier to reach good solutions, and the sensitivity-informed reduction of problem size and pre-conditioning improve the efficiency, reliability and effectiveness of the multi-objective evolutionary optimization.

We have added the relevant explanations in the revised manuscript.

Comment 10: Line 4 - page 3722 : Change ‘neuron’ to ‘neural’.

Response:

We have changed ‘neuron’ to ‘neural’ in the revised manuscript.

Comment 11: Line 1 - page 3727: Change ‘Since MOEA search is stochastic...’ to ‘Since MOEA uses random-based search...’

Response:

We have re-phrased the sentence to “Since MOEA uses random-based search...” in the revised manuscript.

Comment 12: Line 26 – page 3731: I don’t understand the term ‘diminishing returns’ here. Perhaps it can be changed to ‘diminishing values’?

Response:

We have changed ‘diminishing returns’ to ‘diminishing values’ in the revised manuscript.

Comment 13: When using the numbers for storage volumes or catchment areas in the presented cases, I would suggest to use values expressed as 10^3 or 10^6 , etc (thousands, millions, etc) rather than other expressions like 10^5 or 10^8 . I think it is easier for readers to get quickly the impression about the actual sizes.

Response:

The expressions have been changed in the revised manuscript.

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List of all relevant changes made in the revised manuscript

- [1] We have changed the term “problem decomposition” into the term “dimension reduction” throughout the revised manuscript including the title.
- [2] We have added the description of relevant algorithms that seek the optimal reservoir operation policy as trajectories through time (e.g. Dynamic Programming, Stochastic Dynamic Programming and more recently Reinforcement learning and others) on lines 51-74 in the revised manuscript.
- [3] We have changed ‘neuron’ to ‘neural’ on line 108 in the revised manuscript.
- [4] We have made clear that Fig. 1 is just an illustration of rule curves for Dahuofang reservoir on lines 144-145 in the revised manuscript.
- [5] We have clarified the explanation for Fig. 1 on lines 146-159, lines 162-165 and lines 168-173 in the revised manuscript.
- [6] More clarifications regarding Equation (1) on line 196 that introduces the general formulation of the objective functions are added on lines 175-180, lines 189-193, lines 203-209 and lines 217-219 in the revised manuscript.
- [7] We have re-phrased the sentence “Since MOEA search is stochastic...” to “Since MOEA uses random-based search...” on line 269 in the revised manuscript.
- [8] We have corrected the sentence “...needs to translate...” to “The additive ε -indicator measures the smallest distance that a solution set needs to be translated to completely dominate the reference set” on lines 276-278 in the revised manuscript.
- [9] We have corrected the expression for the area of Liaoning province in China to $146 \times 10^3 \text{ km}^2$ on line 323 in the revised manuscript.
- [10] We have provided the clarifications and explanations regarding the rule curves for Dahuofang reservoir from the final Pareto fronts and the sensitivity-related results, which are presented in Fig. 8 (S2) and Figure 4, on lines 378-380 and lines 446-495 in the revised manuscript.
- [11] We have provided the clarifications and explanations regarding the identification of the most sensitive decision variables from Fig. 4 and Fig. 9 on lines 386-390 and lines 533-535 in the revised manuscript.

[12] We have provided the clarifications and explanations regarding the initial value settings of the insensitive variables for the pre-conditioned optimization and the full search on lines 394-396, line 399, lines 538-540 and line 546 in the revised manuscript.

[13] We have changed ‘diminishing returns’ to ‘diminishing values’ on line 407 in the revised manuscript.

[14] We have added the comparisons among the optimized solutions from the final Pareto fronts, including industry-favoring solution (S0), agriculture-favoring solution (S1) and compromised solution (S2) on lines 496-517 in the revised manuscript, where the comparisons of water shortage indices among different solutions are shown in Table 3, and the optimal rule curves for different solutions are shown in Fig. 8.

[15] We have provided some thoughts regarding the expectations for similar efficiency gains and the large efficiency gains reported case-specific in other water-related optimization problems on lines 618-643 in the revised manuscript.

Improving multi-objective reservoir operation optimization with sensitivity-informed dimension reduction

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Abstract

This study investigates the effectiveness of a sensitivity-informed method for multi-objective operation of reservoir systems, which uses global sensitivity analysis as a screening tool to reduce the computational demands. Sobol's method is used to screen insensitive decision variables and guide the formulation of the optimization problems with a significantly reduced number of decision variables. This sensitivity-informed method dramatically reduces the computational demands required for attaining high quality approximations of optimal tradeoff relationships between conflicting design objectives. The search results obtained from the reduced complexity multi-objective reservoir operation problems are then used to pre-condition the full search of the original optimization problem. In two case studies, the Dahuofang reservoir and the inter-basin multi-reservoir system in Liaoning province, China, sensitivity analysis results show that reservoir performance is strongly controlled by a small proportion of decision variables. Sensitivity-informed dimension reduction and pre-conditioning are evaluated in their ability to improve the efficiency and effectiveness of multi-objective evolutionary optimization. Overall, this study illustrates the efficiency and effectiveness of the sensitivity-informed method and the use of global sensitivity analysis to inform dimension reduction of optimization problems when solving the complex multi-objective reservoir operation problems.

Keywords water supply; complexity reduction; multi-objective optimization; preconditioning; sensitivity analysis; reservoir operation

1 Introduction

Reservoirs are often operated considering a number of conflicting objectives (such as different water uses) related to environmental, economic and public services. The optimization of Reservoir Operation Systems (ROS) has attracted substantial attention over the past several decades. In China and many other countries, reservoirs are operated according to reservoir operation rule curves which are established at the planning/design stage to provide long-term operation guidelines for reservoir management to meet expected water demands. Reservoir operation rule curves usually consist of a series of storage volumes or levels at different periods (Liu et al., 2011a and 2011b).

In order to solve the ROS problem, there are different approaches, such as implicit stochastic optimization (ISO), explicit stochastic optimization (ESO), and parameter-simulation-optimization (PSO) (Celeste and Billib, 2009). ISO uses deterministic optimization, e.g., dynamic programming, to determine a set of optimal releases based on the current reservoir storage and equally likely inflow scenarios (Young, 1967; Karamouz and Houck, 1982; Castelletti et al., 2012; François et al., 2014). Instead the use of equally likely inflow scenarios, ESO incorporates inflow probability directly into the optimization process, including stochastic dynamic programming and Bayesian methods (Huang et al., 1991; Tejada-Guibert et al., 1995; Powell, 2007; Goor et al., 2010; Xu et al., 2014). However, many challenges remain in application of these two approaches due to their complexity and ability to conflicting objectives (Yeh, 1985; Simonovic, 1992; Wurbs, 1993; Teegavarapu and

Simonovic, 2001; Labadie, 2004).

In a different way, PSO predefines a rule curve shape and then utilizes optimization algorithms to obtain the combination of rule curve parameters that provides the best reservoir operating performance under possible inflow scenarios or a long inflow series (Nalbantis and Koutsoyiannis, 1997; Oliveira and Loucks, 1997). In this way, most stochastic aspects of the problem, including spatial and temporal correlations of unregulated inflows, are implicitly included, and reservoir rule curves could be derived directly with genetic algorithms and other direct search methods (Koutsoyiannis and Economou, 2003; Labadie, 2004). Because PSO reduces the curse of dimensionality problem in ISO and ESO, it is widely used in reservoir operation optimization (Chen, 2003; Chang et al., 2005; Momtahan and Dariane, 2007). In this study, the PSO-based approach is used to solve the ROS problem.

In the PSO procedure to solve the ROS problem, the values of storage volumes or levels in reservoir operation rule curves are optimized to achieve one or more objectives directly. Quite often, there are multiple curves, related to different purposes of reservoir operation. The dimension of a ROS problem depends on the number of the curves and the number of time periods. For a cascaded reservoir system, the dimension can be very large, which increases the complexity and problem difficulty and poses a significant challenge for most search tools currently available (Labadie, 2004; Draper and Lund, 2004; Sadegh et al., 2010; Zhao et al., 2014).

In the context of multi-objective optimal operation of ROS, there is not one single operating policy that improves simultaneously all the objectives and a set of

non-dominating Pareto optimal solutions are normally obtained. The traditional approach to multi-objective optimal reservoir operation is to reformulate the multi-objective problem as a single objective problem through the use of some scalarization methods, such as the weighted sum method (Tu et al., 2003 and 2008; Shiau, 2011). This method has been developed to repeatedly solve the single objective problem using different sets of weights so that a set of Pareto-optimal solutions to the original multi-objective problem could be obtained (Srinivasan and Philipose, 1998; Shiau and Lee, 2005). Another well-known method is the ϵ -constraint method (Ko et al., 1997; Mousavi and Ramamurthy, 2000; Shirangi et al., 2008): all the objectives but one are converted into constraints and the level of satisfaction of the constraints is optimized to obtain a set of Pareto-optimal solutions. However, with the increase in problem complexity (i.e., the number of objectives or decision variables), both approaches become inefficient and ineffective in deriving the Pareto-optimal solutions.

In the last several decades, bio-inspired algorithms and tools have been developed to directly solve multi-objective optimization problems by simultaneously handling all the objectives (Nicklow et al., 2010). In particular, multi-objective evolutionary algorithms (MOEA) have been increasingly applied to the optimal reservoir operation problems, with intent of revealing tradeoff relationships between conflicting objectives. Suen and Eheart (2006) used the non-dominated sorting genetic algorithm (NSGAII) to find the Pareto set of operating rules that provides decision makers with the optimal trade-off between human demands and ecological flow requirements.

Zhang et al. (2013b) used a multi-objective adaptive differential evolution combined with chaotic **neural** networks to provide optimal trade-offs for multi-objective long-term reservoir operation problems, balancing hydropower operation and the requirement of reservoir ecological environment. Chang et al. (2013) used an adjustable particle swarm optimization – genetic algorithm (PSO-GA) hybrid algorithm to minimize water shortages and maximize hydro-power production in management of Tao River water resources.

However, significant challenges remain for using MOEAs in large, real-world ROS applications. The high dimensionality of ROS problems makes it very difficult for MOEAs to identify ‘optimal or near optimal’ solutions with the computing resources that are typically available in practice. Thus the primary aim of this study is to investigate the effectiveness of a sensitivity-informed optimization methodology for multi-objective reservoir operation, which uses sensitivity analysis results to reduce the dimension of the optimization problems, and thus improves the search efficiency in solving these problems. This framework is based on the previous study by Fu et al. (2012), which developed a framework **for dimension reduction of optimization problems** that can dramatically reduce the computational demands required to obtain high quality solutions for optimal design of water distribution systems. The ROS case studies used to demonstrate this framework consider the optimal design of reservoir water supply operation policies. Storage volumes at different time periods on the operation rule curves are used as decision variables. It has been widely recognized that the determination of these decision variables requires

a balance among different ROS objectives. Sobol's sensitivity analysis results are used to form simplified optimization problems considering a small number of sensitive decision variables, which can be solved with a dramatically reduced number of model evaluations to obtain Pareto approximate solutions. These Pareto approximate solutions are then used to pre-condition a full search by serving as starting points for the multi-objective evolutionary algorithm. The results from the Dahuofang reservoir and inter-basin multi-reservoir system case studies in Liaoning province, China, whose conflicting objectives are minimization of industry water shortage and minimization of agriculture water shortage, illustrate that sensitivity-informed **dimension reduction** and pre-conditioning provide clear advantages to solve large-scale multi-objective ROS problems effectively.

2 Problem formulation

Most reservoirs in China are operated according to rule curves, i.e., reservoir water supply operation rule curves. Because they are based on actual water storage volumes, they are simple to use. **Fig. 1 shows an illustration of rule curves for Dahuofang reservoir based on 36 10-day periods.**

As we know that water demand could be fully satisfied only when there is sufficient water in reservoir. Water supply operation rule curve, which is used to operate most reservoirs in China, represents the limited storage volume for water supply in each period of a year. In detail, water demand will be fully satisfied when the reservoir storage volume is higher than water supply operation rule curve; whereas

water demand needs to be rationed when the reservoir storage volume is lower than water supply operation rule curve. In general, a reservoir has more than one water supply target, and there is one to one correspondence between water supply rule curve and water supply target. The water supply with lower priority will be limited prior to the water supply with higher priority when the reservoir storage volume is not sufficient. To reflect the phenomenon that different water demands can have different reliability requirements and thus different levels of priority in practice, the operation rule curve for the water supply with the lower priority is located above the operation rule curve for the water supply with the higher priority.

Fig. 1 shows water supply operation rule curves for agriculture and industry where the maximum storage is smaller in the middle due to the flood control requirements in wet seasons. In Fig. 1, the red line with circle represent water supply rule curve for agriculture, the green line with triangle represent water supply rule curve for industry. The water supply rule curve for agriculture with lower priority is located above the water supply rule curve for industry with higher priority. The water storage available between the minimum and maximum storages is divided into three parts: zone 1, zone 2 and zone 3 by the water supply rule curves for agriculture and industry.

Specifically, both the agricultural demand D_1 and the industrial demand D_2 could be fully satisfied when the actual water storage is in zone 1, which is above the water supply rule curve for agriculture. When the actual water storage is in zone 2, the industrial demand could be fully satisfied, and the agricultural demand has to be rationed. Both the agricultural demand and the industrial demand have to be rationed

when the actual water storage is in zone 3. The water supply rule for a specific water user consists of one water supply rule curve and rationing factors that indicate the reliability and priority of the water user. The rationing factors used to determine the amount of water supply for different water demands can be either assigned according to the experts' knowledge or determined by optimization (Shih and ReVelle, 1995). In this paper, rationing factors are given at the reservoir's design stage according to the tolerable elastic range of each water user in which the damage caused by rationing water supply is limited. Assuming that the specified water rationing factor α_1 is applied to the water supply rule curve for agriculture in Fig. 1, the agricultural demand D_1 could be fully supplied without rationing when the actual water storage is in zone 1, however, when the water storage is in zone 2 or zone 3, the agricultural demand has to be rationed, i.e., $\alpha_1 * D_1$. Similarly, assuming that the specified water rationing factor α_2 is applied to the water supply rule curve for industry in Fig. 1, the industrial demand D_2 could be fully supplied without rationing when the actual water storage is in zone 1 or zone 2, however, when the water storage is in zone 3, the industrial demand has to be rationed, i.e., $\alpha_2 * D_2$.

To provide long-term operation guidelines for reservoir management to meet expected water demands for future planning years, the projected water demands and long-term historical inflow are used. The optimization objective for water supply operation rule curves is to minimize water shortages during the long-term historical period. The ROS design problem is formulated as a multi-objective optimization problem, i.e., minimizing multiple objectives simultaneously. In this paper, the

objectives are to minimize industry and agriculture water shortages:

$$\min f_i(\mathbf{x}) = SI_i = \frac{100}{N} \sum_{j=1}^N \left(\frac{D_{i,j} - W_{i,j}(\mathbf{x})}{D_{i,j}} \right)^2 \quad (1)$$

where \mathbf{x} is the vector of decision variables, i.e., the water storages at different periods on a water-supply rule curve; SI_i is the shortage index for water demand i (agricultural water demand when $i = 1$, industrial water demand when $i = 2$), which measures the average annual shortage occurred during N years, and is used as an indicator to reflect water supply efficiency; N is the total number of years simulated; $D_{i,j}$ is the demand for water demand i during the j th year; $W_{i,j}(\mathbf{x})$ is the actually delivered water for water demand i during the j th year. The term $W_{i,j}(\mathbf{x})$ is calculated below using agricultural water demand ($i = 1$) as an example. If the actual water storage is above the water supply rule curve for agricultural water demand ($i = 1$) at period t in a year, the delivered water at period t is its full demand without being rationed, $D_{1,t}$. If the actual water storage is below the water supply rule curve for agricultural water demand at period t , the delivered water for agricultural water demand at period t is its rationed demands, $\alpha_1 * D_{1,t}$.

For the ROS optimization problem, the mass balance equations are:

$$S_{t+1} - S_t = I_t - R_t - SU_t - E_t \quad (2)$$

$$R_t = g(\mathbf{x}), SU_t = k(\mathbf{x}), E_t = e(\mathbf{x}) \quad (3)$$

$$ST_t^{\min} \leq S_t \leq ST_t^{\max}, ST_t^{\min} \leq \mathbf{x} \leq ST_t^{\max} \quad (4)$$

where S_t is the initial water storage at the beginning of period t ; S_{t+1} is the ending water storage at the end of period t ; I_t, R_t, SU_t and E_t are inflow, delivery for water use, spill and evapotranspiration loss, respectively; and ST_t^{\max} and ST_t^{\min}

are the maximum and minimum storage, respectively. Additionally, because $W_{i,j}(x)$ in Equation (1) is the actually delivered water for water demand i during the j th year, the sum of R during the j th year equals to $W_{1,j}(x) + W_{2,j}(x)$.

3 Methodology

Pre-conditioning is a technique that uses a set of known good solutions as starting points to improve the search process of optimization problems (Nicklow et al., 2010). It is very challenging in determining good initial solutions, and different techniques including the domain knowledge can be used. This study utilizes a sensitivity-informed dimension reduction to develop simpler search problems that consider only a small number of highly sensitive decisions. The results from these simplified search problems can be used to successively pre-condition search for larger, more complex formulations of ROS design problems. The ϵ -NSGAI, a popular multi-objective evolutionary algorithm, is chosen as it has been shown effective for many engineering optimization problems (Kollat and Reed, 2006; Tang et al., 2006; Kollat and Reed, 2007). For the two-objectives (ϵ_{SL_1} and ϵ_{SL_2}) considered in this paper, their epsilon values in ϵ -NSGAI were chosen based on reasonable and practical requirements and were both set to 0.01. According to the study by Fu et al. (2012), the sensitivity-informed methodology, as shown in Fig. 2, has the following steps:

1. Perform a sensitivity analysis using Sobol's method to calculate the sensitivity indices of all decision variables regarding the ROS performance measure;

2. Define a simplified problem that considers only the most sensitive decision variables by imposing a user specified threshold (or classification) of sensitivity;

3. Solve the simplified problem using ε -NSGAII with a small number of model simulations;

4. Solve the original problem using ε -NSGAII with the Pareto optimal solutions from the simplified problem fed into the initial population.

3.1 Sobol's sensitivity analysis

Sobol's method was chosen for sensitivity analysis because it can provide a detailed description of how individual variables and their interactions impact model performance (Tang et al., 2007b; Zhang et al., 2013a). A model could be represented in the following functional form:

$$y = f(\mathbf{x}) = f(x_1, \dots, x_p) \quad (5)$$

where y is the goodness-of-fit metric of model output, and $\mathbf{x} = (x_1, \dots, x_p)$ is the parameter set. Sobol's method is a variance based method, in which the total variance of model output, $D(y)$, is decomposed into component variances from individual variables and their interactions:

$$D(y) = \sum_i D_i + \sum_{i < j} D_{ij} + \sum_{i < j < k} D_{ijk} + \dots + D_{12\dots m} \quad (6)$$

where D_i is the amount of variance due to the i th variable x_i , and D_{ij} is the amount of variance from the interaction between x_i and x_j . The model sensitivity resulting from each variable can be measured using the Sobol's sensitivity indices of different orders:

$$\text{First-order index: } S_i = \frac{D_i}{D} \quad (7)$$

$$\text{Second-order index: } S_{ij} = \frac{D_{ij}}{D} \quad (8)$$

$$\text{Total-order index: } S_{Ti} = 1 - \frac{D_{\sim i}}{D} \quad (9)$$

where $D_{\sim i}$ is the amount of variance from all the variables except for x_i , the first-order index S_i measures the sensitivity from the main effect of x_i , the second-order index S_{ij} measures the sensitivity resulting from the interactions between x_i and x_j , and the total-order index S_{Ti} represents the main effect of x_i and its interactions with all the other variables.

3.2 Performance metrics

Since MOEA uses random-based search, performance metrics are used in this study to compare the quality of the approximation sets derived from replicate multi-objective evolutionary algorithm runs. Three indicators were selected: the generational distance (Veldhuizen and Lamont, 1998), the additive ϵ -indicator (Zitzler et al., 2003), and the hypervolume indicator (Zitzler and Thiele, 1998).

The generational distance measures the average Euclidean distance from solutions in an approximation set to the nearest solution in the reference set, and indicates perfect performance with zero. The additive ϵ -indicator measures the smallest distance that a solution set needs to be translated to completely dominate the reference set. Again, smaller values of this indicator are desirable as this indicates a closer approximation to the reference set.

The hypervolume indicator, also known as the S metric or the Lebesgue measure, measures the size of the region of objective space dominated by a set of solutions. The hypervolume not only indicates the closeness of the solutions to the optimal set, but

also captures the spread of the solutions over the objective space. The indicator is normally calculated as the volume difference between a solution set derived from an optimization algorithm and a reference solution set. In this study, the worst case solution is chosen as reference. For example, the worst solution is (1, 1) for two minimization objectives in the normalized objective space. Thus larger hypervolume indicator values indicate improved solution quality and imply a larger distance from the worst solution.

4 Case study

Two case studies of increasing complexity are used to demonstrate the advantages of the sensitivity-informed methodology: (1) the Dahuofang reservoir, and (2) the inter-basin multi-reservoir system in Liaoning province, China. The inter-basin multi-reservoir system test case is a more complex ROS problem with Dahuofang, Guanyinge and Shenwo reservoirs. In the two ROS problems, the reference sets were obtained from all the Pareto optimal solutions across a total of 10 random seed trials, each of which was run for a maximum number of function evaluations (NFE) of 500,000. Additionally, the industrial and agricultural water demands in the future planning year, i.e., 2030, and the historical inflow from 1956 to 2006 were used to optimize reservoir operation and meet future expected water demands in the two case studies.

4.1 Dahuofang reservoir

The Dahuofang reservoir is located in the main stream of Hun River, in Liaoning

province, Northeast China. The Dahuofang reservoir basin drains an area of 5437 km², and within the basin the total length of Hun River is approximately 169 km. The main purposes of the Dahuofang reservoir are industrial water supply and agricultural water supply to central cities in Liaoning province. The reservoir characteristics and yearly average inflow are illustrated in Table 1.

The Dahuofang ROS problem is formulated as follows: the objectives are minimization of industrial shortage index and minimization of agricultural shortage index as described in Equation (1); the decision variables include storage volumes on the industrial and agricultural curves. For the industrial curve, a year is divided into 24 time periods (with ten days as the scheduling time step from April to September, and one month as the scheduling time step in the remaining months). Thus there are twenty-four decision variables for industrial water supply. The agricultural water supply occurs only in the periods from the second ten-day of April to the first ten-day of September, thus there are fifteen decision variables for agricultural water supply. In total, there are thirty-nine decision variables.

4.2 Inter-basin multi-reservoir system

As shown in Fig. 3, Dahuofang, Guanyinge and Shenwo reservoirs compose the inter-basin multi-reservoir system in Liaoning province, China.

Liaoning province in China covers an area of 146×10^3 km² with an extremely uneven distribution of rainfall in space. The average amount of annual precipitation decreases from 1100 mm in east to 600 mm in west (WMR-PRC, 2008). However, the population, industries, and agricultural areas mainly concentrate in the western parts.

Therefore, it is critical to develop the best water supply rules for the inter-basin multi-reservoir system to decrease the risk of water shortages caused by the mismatch of water supplies and water demands in both water deficit regions and water surplus regions. Developing inter-basin multi-reservoir water supply operation rules has been promoted as a long-term strategy for Liaoning province to meet the increasing water demands in water shortage areas. In the inter-basin multi-reservoir system of Liaoning province, the abundant water in Dahuofang, Guanying and Shenwo reservoirs is diverted downstream to meet the water demands in water shortage areas, especially the region between Daliaohoukou and Sanhekou hydrological stations.

The main purposes of the inter-basin multi-reservoir system are industrial water supply and agricultural water supply to eight cities (Shenyang, Fushun, Anshan, Liaoyang, Panjin, Yingkou, Benxi and Dalian) of Liaoning province, and environmental water demands need to be satisfied fully. The characteristics of each reservoir in the inter-basin multi-reservoir system are illustrated in Table 2.

The flood season runs from July to September, during which the inflow takes up a large part of the annual inflow. The active storage capacities of Dahuofang and Shenwo reservoirs reduce significantly during flood season for the flood control.

The inter-basin multi-reservoir operation system problem is formulated as follows: the objectives are minimization of industrial shortage index and minimization of agricultural shortage index as described in Equation (1). Regarding Shenwo reservoir, which has the same water supply operation rule curve features as Dahuofang reservoir, the decision variables include storage volumes on the industrial and agricultural

curves and there are thirty-nine decision variables. Regarding Guanyinge reservoir, the decision variables include storage volumes on the industrial curve and water transferring curve due to the requirement of exporting water from Guanyinge reservoir to Shenwo reservoir in the inter-basin multi-reservoir system, which is similar to the water supply operation rule curve for industrial water demand, and there are forty-eight decision variables. Therefore, the inter-basin multi-reservoir system has six rule curves and $39 \times 2 + 48 = 126$ decision variables in total.

5 Results and discussions

5.1 Dahuofang reservoir

In the Dahuofang reservoir case study, a set of 2000 Latin Hypercube samples were used per decision variable yielding a total number of $2000 \times (39 + 2) = 82000$ model simulations used to compute Sobol's indices. Following the recommendations of Tang et al. (2007a, b) boot-strapping the Sobol' indices showed that 2000 samples per decision variable were sufficient to attain stable rankings of global sensitivity.

The first-order indices representing the individual contributions of each variable to the variance of the objectives are shown in blue in Fig. 4. The total-order indices representing individual and interactive impacts on the variance of the objectives are represented by the total height of bars. Agr4_2 represents decision variable responding to water storage volume on the agricultural curve at the second ten days of April and ind3_3 represents decision variable responding to water storage volume on

the industrial curve at the last ten days of March, and so on. Considering the shortage index for the industrial water demand, the water storages at time periods ind1, ind2, ind3, ind10, ind11, and ind12, i.e., the water storages at time periods 1, 2, 3, 10, 11, and 12 of water supply operation rule curves for industrial water demand are the most sensitive variables, accounting for almost 100% of the total variance. Considering the agricultural shortage index, the water storages at time periods from agr4-2 to agr5-3, i.e., the water storages at the first five time periods of water supply operation rule curves for agricultural water demand are the most sensitive variables. The explanation for the most sensitive variables in water supply operation rule curves for industrial and agricultural water demands will be provided in section 5.1.3.

5.1.1 Simplified problems

Building on the sensitivity results shown in Fig. 4, one simplified version of the Dahuofang ROS problem is formulated: only 11-periods are considered for optimization, i.e., time periods ind1, ind2, ind3, ind10, ind11, and ind12 for industrial curve and agr4-2, agr4-3, agr5-1, agr5-2, and agr5-3 for agricultural curve based on a total-order Sobol's index threshold of greater than 10%. The threshold is subjective and its ease-of-satisfaction decreases with increasing number of parameters or parameter interactions. In all of the results for the Sobol's method, parameters classified as the most sensitive contribute, on average, at least 10 percent of the overall model variance (Tang et al., 2007a, b). The full search 39-period problem serves as the performance baseline relative to the reduced complexity problem.

5.1.2 Pre-conditioned optimization

In this section, the pre-conditioning methodology is demonstrated using the 11-period simplification of the Dahuofang ROS test case from the prior section, while the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem.

Using the sensitivity-informed methodology, the 11-period case was first solved using ϵ -NSGAI with a maximum NFE of 2000, and the Pareto optimal solutions combined with the constant insensitive decision variables were then used as starting points to start a complete new search with a maximum NFE of 498,000. The standard search using ϵ -NSGAI was set to a maximum NFE of 500,000 so that the two methods have the same NFE used for search. In this case, 10 random seed trials were used given the computing resources available. The search traces in Fig. 5 show for all three metrics (generational distance, additive epsilon indicator, and hypervolume) that the complexity-reduced case can reliably approximate their portions of the industrial and agricultural water shortage tradeoff given their dramatically reduced search periods. All three metrics show diminishing values at the end of the reduced search periods. The pre-conditioning results are shown in Fig. 5 in red search traces continuing from the blue reduced complexity search results.

Fig. 5 clearly highlight that the sensitivity-informed pre-condition problems dramatically enhance search efficiency in terms of the generational distance, additive epsilon indicator, and hypervolume metrics. Overall, sensitivity-informed dimension reduction and pre-conditioning yield strong efficiency gains and more reliable search (i.e., narrower band widths on search traces) for the Dahuofang ROS test case.

Fig. 6(a) shows Pareto fronts from a NFE of 3000, 5000 and 8000 in the evolution process of one random seed trial. In the case of the pre-conditioned search, the solutions from 3000, 5000 and 8000 evaluations are much better than the corresponding solutions in the case of standard baseline search. The results show that the Pareto approximate front of the pre-conditioned search is much wider than that of the standard search, and clearly dominates that of the standard search in all the regions across the entire objective space.

Fig. 6(b) shows the best and worst Pareto fronts from a NFE of 500,000 and 8000 in the evolution process of ten seed trials. In the case of the pre-conditioned search, the best solutions from 500,000 evaluations are better than the corresponding solutions in the case of standard baseline search. Although it is obvious that there are not many differences between solutions obtained from pre-conditioned search and solutions from standard baseline search due to the complexity of the problem, the best Pareto fronts from a NFE of 8000 in the case of the pre-condition search are approximate the same as the best Pareto fronts from a NFE of 500,000 in the case of the standard baseline search.

Fig. 7 shows the computational savings for two thresholds of hypervolume values 0.80 and 0.85 in the evolution process of each seed trial. In both cases of the thresholds of hypervolume values 0.80 and 0.85, NFE of the pre-conditioned search is less than standard baseline search for each seed. In the case of the threshold of hypervolume value 0.80, the average NFEs of full search and pre-conditioned full search are approximately 94,564 and 25,083 for one seed run respectively, and the

computation is saved by 73.48%. Although the NFE of Sobol's analysis is 82,000, the average NFEs of pre-conditioned full search is approximately $25,083 + 82,000/10 = 33,283$ for each seed run, and the computational saving is 64.80%.

Similarly, in the case of the threshold of hypervolume value 0.85, which is extremely difficult to achieve, the average NFEs of full search and pre-conditioned full search are approximately 214,049 and 105,060 for each seed run respectively, and the computation is saved by 50.92%. When the computation demand by Sobol's analysis is considered, the computational saving is still 47.09%.

5.1.3 Optimal operation rule curves

The rule curves for Dahuofang reservoir from the final Pareto fronts based on the projected water demands and long-term historical inflow are shown in Fig. 8 (S2). The effectiveness and reasonability of the rule curves for Dahuofang reservoir are analyzed as follows.

Firstly, the optimal operational rule curves in Fig. 8 (S2) have the same characteristics as they are used in practice. During the pre-flood season (from April to June), the curves gradually become lower so that they can reduce the probability of limiting water supply and empty the reservoir storage for the flood season (from July to early September). During the flood season, the curves also stay in low positions owing to the massive reservoir inflow and the requirement of flood control, so that it is beneficial to supply as much water as possible. However, during the season from mid-September to March, the curves remain high, especially from mid-September to October, in order to increase the probability of limiting water supply and retaining

459 enough water for later periods to avoid severe water-supply shortages as drought
460 occurs.

461 Secondly, Fig. 8 (S2) shows that different water demands occur at different
462 periods, e.g., industrial water demand occurs throughout the whole year, and
463 agricultural water demand occurs only at the periods from the second ten-day of April
464 to the first ten-day of September. Specially, during the flood season, there are still
465 agricultural water demands due to temporal and spatial variations of rainfall though
466 they are significantly reduced. Also note that the water supply curves are developed
467 based on a historical, long-term rainfall series and the projected demands are also
468 based on historical demands, covering stochastic uncertainties in demands and
469 rainfalls. Due to the higher priority of industrial water supply than agricultural water
470 supply, the industrial water supply curve is more close to minimum storage
471 throughout the year than the agricultural water supply curve. Due to the conflicting
472 relationship between industrial and agricultural water demands, the industrial water
473 supply curve is higher during the non-flood season. Thus, if the industrial water
474 supply curve is too low during the non-flood season from January to April, which
475 implies that the industrial water demand is satisfied sufficiently, there would not be
476 enough water supplied for the agricultural water demand in the same year. Similarly,
477 if the industrial water supply curve is too low during the non-flood season from
478 September to December, there would not be enough water supplied for the
479 agricultural water demand in the next one or more years.

480 Thirdly, the inflow and industrial water demands are relatively stable during the

non-flood seasons from January to March and from October to December, so one month is taken as the scheduling time step, which is in accordance with the requirement of Dahuofang reservoir operation in practice. Due to the larger amount of industrial water demand in periods 1, 2, 3, 10, 11 and 12 (January-March and October-December) than other periods, the water storages at these time periods are very important to industrial water supply, making them the most sensitive variables. Because the agricultural water demand is very high during the non-flood period from April to May, the agricultural water supply curve at this time period is higher, and the water storages at time periods from agr4-2 to agr5-3, i.e., the water storages at the first five time periods of water supply operation rule curve for agricultural water demand, are the most important variables. On the other hand, in practice, if the agricultural water demand could not be satisfied at the first few periods of water supply operation rule curve, the agricultural water supply at each period throughout the year would be limited, i.e., the interactive effects from variables are noticeable at time periods from agr4-2 to agr5-3.

Additionally, comparisons are made among the optimized solutions from the final Pareto fronts, including industry-favoring solution (S0), agriculture-favoring solution (S1) and compromised solution (S2). The comparisons of water shortage indices among different solutions are shown in Table 3, and the optimal rule curves for different solutions are shown in Fig. 8.

It could be seen from Table 3 and Fig. 8 that there are larger differences among different solutions. With industry-favoring solution (S0), the agricultural water supply

curve at the period from April to May is the highest among the three solutions. Because the agricultural water demand is very high during the non-flood period from April to May, the highest position of agricultural water supply curve at these periods could cause that the agricultural water demand would not be satisfied at the first few periods of agricultural water supply operation rule curve, and the agricultural water supply at each period throughout the year would be limited easily. Therefore, in S0, the industrial water demand could be fully satisfied through limiting agricultural water supply to a large extend, and lowering the industrial water supply curve; industrial and agricultural water shortage indices are 0.000 and 3.550, respectively. Opposite to S0, the agricultural water demand in S1 could be satisfied largely through lowering the agricultural water supply curve on the period from April to May and raising the industrial water supply curve; and industrial and agricultural water shortage indices are 0.020 and 1.380, respectively. Compared with solutions S0 and S1, two objectives are balanced in compromised solution (S2), where industrial and agricultural water shortage indices are 0.007 and 1.932, respectively.

5.2 Inter-basin multi-reservoir system

5.2.1 Sensitivity analysis

Similar to the Dahuofang case study, a set of 2000 Latin Hypercube samples were used per decision variable yielding a total number of $2000 \times (126 + 2) = 256,000$ model simulations to compute Sobol's indices in this case study.

The first-order and total-order indices for 126 decision variables are shown in Fig.

9. Similar to the results obtained from the Dahuofang ROS Problem in Fig. 4, the variance in the two objectives, i.e., industrial and agricultural shortage indices, are largely controlled by the water storages at time periods from agr4-2 to agr5-3 of Shenwo reservoir water supply operation rule curves for agricultural water demand, the water storages at time periods from agr4-2 to agr5-3 of Dahuofang reservoir water supply operation rule curves for agricultural water demand, the water storages at time periods ind1, ind2, ind3, ind7-1, ind10, ind11, and ind12 of Dahuofang reservoir water supply operation rule curves for industrial water demand based on a total-order Sobol's index threshold of greater than 3%, which is subjective and its ease-of-satisfaction decreases with increasing numbers of parameters or parameter interactions. These 17 time periods are obvious candidates for decomposing the original optimization problem and formulating a pre-conditioning problem. Therefore, the simplified problem is defined from the original design problem with the 109 intensive time periods removed, while the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem. It should be noted that the increased interactions across sensitive time periods in this test case. These interactions verify that this problem represents a far more challenging search problem.

5.2.2 Pre-conditioned optimization

Using the sensitivity-informed methodology, the simplified problem was first solved using ϵ -NSGAI with a maximum NFE of 5000, and the Pareto optimal solutions combined with the constant insensitive decision variables were then used as

starting points to start a complete new search with a maximum NFE of 495,000. The standard search using ϵ -NSGAII was set to a maximum NFE of 500,000 so that the two methods have the same NFE used for search. In this case, 10 random seed trials are used given the computing resources available. Similar to the results obtained from the Dahuofang ROS problem in Fig. 5, the search traces in Fig. 10 show all three metrics (generational distance, additive epsilon indicator, and hypervolume) that represent performance metrics for the inter-basin multi-reservoir water supply operation system problem. Similarly, the pre-conditioning results are shown in Fig. 10 in red search traces continuing from the blue reduced complexity search results. It is clear that the sensitivity-informed pre-condition problems enhance search efficiency in terms of the generational distance, additive epsilon indicator, and hypervolume metrics. However, with the increase in problem complexity in comparison to the first case study (i.e., the number of decision variables from 39 to 126), the search of ROS optimization problem becomes more difficult, and so the metrics obtained from pre-conditioned search are not improved greatly compared with the standard baseline search and the pre-conditioning results shown in Fig. 10 are as good as the results shown in Fig. 5.

Fig. 11(a) shows Pareto fronts from a NFE of 6000, 8000 and 10,000 in the evolution process of one random seed trial. In the case of the pre-conditioned search, the solutions from the three NFE snapshots are much better than those from standard baseline search. Similar to Fig. 6(a), the results show that the Pareto approximate front of the pre-conditioned search is much wider than that of the standard search, and

clearly dominates that of the standard search in all the regions across the entire objective space. Additionally, in the case of the pre-conditioned search, the solutions from 6000 evaluations are as good as those from 8000 evaluations and 10,000 evaluations. And they are much better than the solutions from the standard baseline search. It should be noted that the slow progress in the Pareto approximate fronts from 6000 to 10,000 evaluations reveals the difficulty of the inter-basin multi-reservoir operation system problem.

Fig. 11(b) shows the best and worst Pareto fronts from a NFE of 500,000 in the evolution process of ten seeds trials. Although it is obvious that the best Pareto approximate front of the pre-conditioned is as good as that of the standard search in all the regions across the entire objective space approximately, the Pareto solutions from 10 trials of the pre-conditioned search have significantly reduced variation, indicating a more reliable performance of the pre-conditioned method. In other words, the results show that the Pareto solution from one random seed trial of the pre-conditioned search is as good as the best solution from ten random seed trials of the standard search. That is to say, in the case of the pre-conditioned search, one random seed trial with a NFE of 500,000 is sufficient to obtain the best set of Pareto solutions, however, in the case of the standard search, ten seed trials with a total of $500,000 * 10 = 5,000,000$ NFE are required to obtain the Pareto solutions. Note that the NFE of Sobol's analysis is 256,000, which is about half of the NFE of one random seed trial. Thus, an improvement in search reliability can significantly reduce the computational demand for a complex search problem such as the multi-reservoir

case study, even when the computation required by sensitivity analysis is included.

5.3 Discussions

The methodology tested in this study aims to reduce the number of decision variables through sensitivity-guided **dimension reduction** to form simplified problems. The optimization results from the two ROS problems show the reduction in decision space can make an impact on the reliability and efficiency of the search algorithm. For the Dahuofang ROS problem, recall that the original optimization problem has 39 decision variables, and the simplified problem has 11 decision variables based on Sobol's analysis. In the case of the inter-basin multi-reservoir operation system, the original optimization problem has 126 decision variables, and the simplified problem has a significantly reduced number of decision variables, i.e., 17. Searching in such significantly reduced space formed by sensitive decision variables makes it much easier to reach good solutions.

Although Sobol's global sensitivity analysis is computationally expensive, it captures the important sensitive information between a large number of variables for ROS models. This is critical for correctly screening insensitive decision variables and guiding the formulation of ROS optimization problems of reduced complexity (i.e., fewer decision variables). For example, in the Dahuofang ROS problem, accounting for the sensitive information, i.e., using total-order or first-order indices, result in a simplified problem for threshold of 10% as shown in Fig. 4. Compared with the standard search, this sensitivity-informed **method** dramatically reduces the

computational demands required for attaining high quality approximations of optimal ROS tradeoffs relationships between conflicting objectives, i.e., the best Pareto fronts from a NFE of 8000 in the case of the pre-condition search are approximately the same as the best Pareto front from a NFE of 500,000 in the case of the standard baseline search.

In reality for a very large and computationally intensive problem, the full search with all the decision variables would likely be so difficult that it may not be optimized sufficiently. However, as shown here, these simplified problems can be used to generate high quality pre-conditioning solutions and thus dramatically improve the computational tractability of complex problems. The framework could be used for solving the complex optimization problems with a large number of decision variables.

For example, Fu et al. (2012) has used the framework for reducing the complexity of the multi-objective optimization problems in water distribution system (WDS), and applied it to two case studies with different levels of complexity - the New York Tunnels rehabilitation problem and the Anytown rehabilitation/redesign problem. For the New York Tunnels network, because the original optimization problem has 21 decision variables (pipes) and each variable has 16 options, the decision space is $16^{21} = 1.934 \times 10^{25}$. The simplified problem with 8 decision variables based on Sobol's analysis have a decision space of $16^8 = 4.295 \times 10^9$. To obtain the same threshold of hypervolume value 0.78 for the New York Tunnels rehabilitation problem, the most the pre-conditioned search need is 60 to 70% fewer NFE relative to the full search through 50 random seed trials. In the case of the Anytown network, the original

problem has a space of 2.859×10^{73} , and the simplified problem has a significantly reduced space of 8.364×10^{38} . Through 50 random seed trials for the Anytown rehabilitation/redesign problem, the full search requires average of 800000 evaluations to reach hypervolume value 0.77, and the pre-conditioned search exceeds hypervolume value 0.8 in all trials in fewer than 200000 evaluations. The results also show that searching in such significantly reduced space formed by sensitive decision variables makes it much easier to reach good solutions, and the sensitivity-informed reduction of problem size and pre-conditioning improve the efficiency, reliability and effectiveness of the multi-objective evolutionary optimization.

It should be noted that the framework for sensitivity-informed dimension reduction of optimization problems is completely independent of multi-objective optimization algorithms, that is, any multi-objective algorithms could be embedded in the framework, including AMALGAM (Vrugt and Robinson, 2007). When dealing with three or more objectives, the formulation of the optimization problems with a significantly reduced number of decision variables will dramatically reduce the computational demands required to attain Pareto approximate solutions in a similar way to the two-objective optimization case studies considered in this paper.

6 Conclusions

This study investigates the effectiveness of a sensitivity-informed optimization method for the ROS multi-objective optimization problems. The method uses a global sensitivity analysis method to screen out insensitive decision variables and thus forms

simplified problems with a significantly reduced number of decision variables. The simplified problems dramatically reduce the computational demands required to attain Pareto approximate solutions, which themselves can then be used to pre-condition and solve the original (i.e., full) optimization problem. This methodology has been tested on two case studies with different levels of complexity- the Dahuofang reservoir and the inter-basin multi-reservoir system in Liaoning province, China. The results obtained demonstrate the following:

1. The sensitivity-informed **dimension reduction** dramatically increases both the computational efficiency and effectiveness of the optimization process when compared to the conventional, full search approach. This is demonstrated in both case studies for both MOEA efficiency (i.e., the NFE required to attain high quality tradeoffs) and effectiveness (i.e., the quality approximations of optimal ROS tradeoffs relationships between conflicting design objectives).

2. The Sobol's method can be used to successfully identify important sensitive information between different decision variables in the ROS optimization problem and it is important to account for interactions between variables when formulating simplified problems.

Overall, this study illustrates the efficiency and effectiveness of the sensitivity-informed method and the use of global sensitivity analysis to inform **dimension reduction**. This method can be used for solving the complex multi-objective optimization problems with a large number of decision variables, such as optimal design of water distribution and urban drainage systems, distributed

hydrological model calibration, multi-reservoir optimal operation and many other
engineering optimization problems.

Acknowledgements

This study was supported by the China Postdoctoral Science Foundation Grants
(2014M561231), and National Natural Science Foundation of China Grants
(51320105010, 51279021, and 51409043).

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Table 1 Reservoir characteristics and yearly average inflow (10⁸ m³)

Reservoir name	Minimum capacity	Utilizable capacity	Flood control capacity	Yearly average inflow
Dahuofang	1.34	14.30	10.00	15.70

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840 Table 2 Characteristics of each reservoir in the inter-basin multi-reservoir system

Reservoir	Active storage (10^8 m^3)		Role in water supply project
	Flood season	Non-flood season	
Dahuofang	10.00	14.30	Supplying water
Guanyinge	14.20	14.20	Supplying water and exporting water to Shenwo
Shenwo	2.14	5.43	Supplying water and importing water from Guanyinge

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Table 3 Comparisons of water shortage indices among different solutions

Solutions	Water Shortage Index (-)	
	Industrial water demand	Agricultural water demand
(S0) Industry-favoring solution	0.000	3.550
(S1) Agriculture-favoring solution	0.020	1.380
(S2) Compromised solution	0.007	1.932

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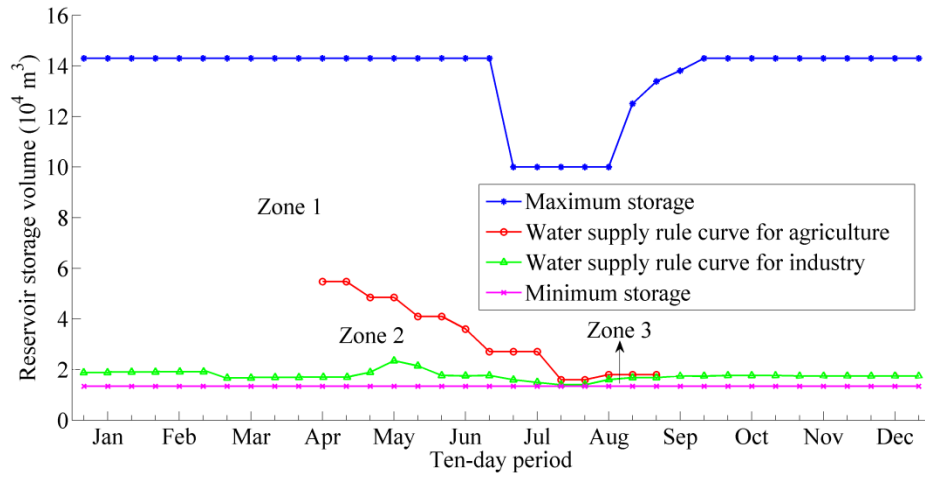


Fig. 1 Reservoir operational rule curves

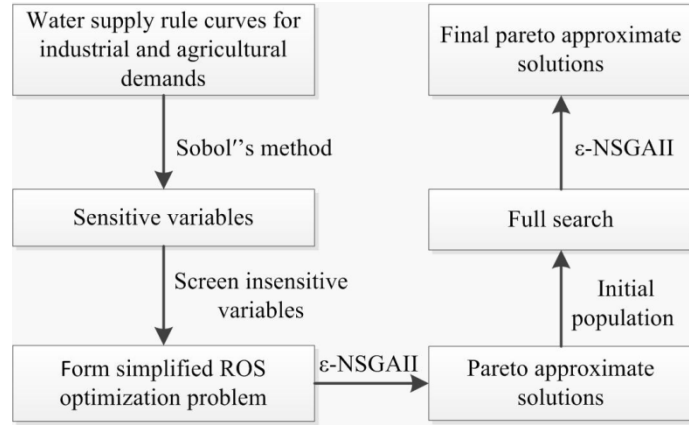


Fig. 2 Flowchart of the sensitivity-informed methodology

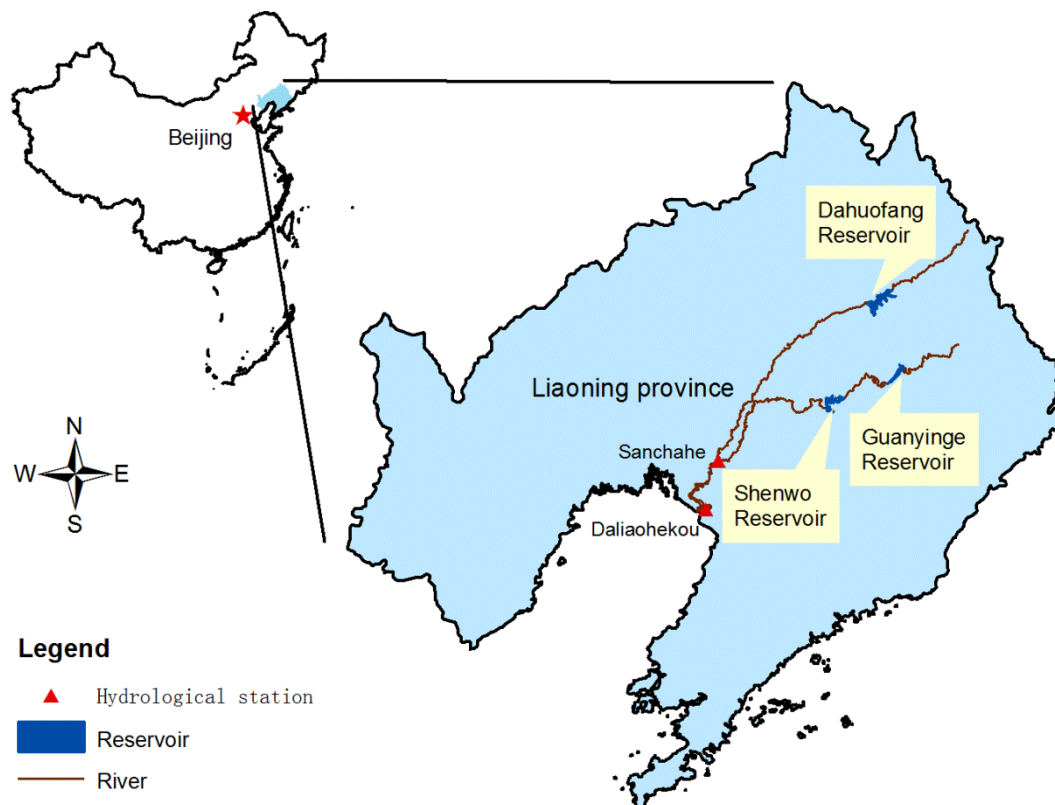


Fig. 3 Layout of the inter-basin multi-reservoir system

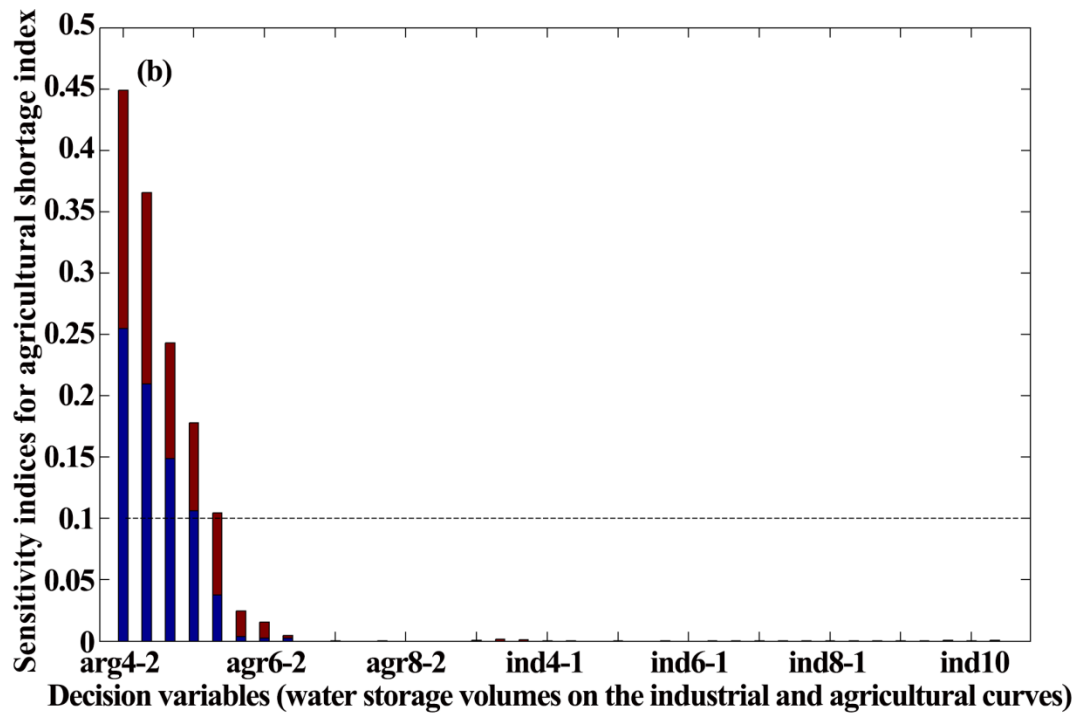
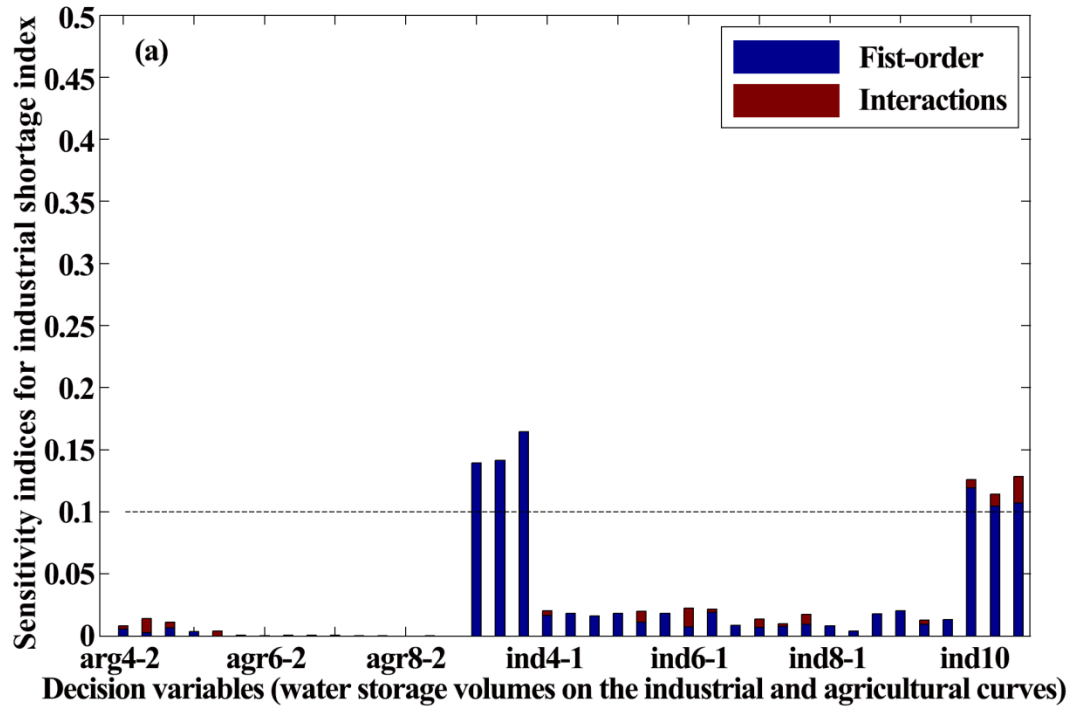


Fig. 4 First-order and total-order indices for the Dahuofang ROS problem regarding (a) industrial shortage index and (b) agricultural shortage index. The x-axis labels represent decision variables (water storage volumes on the industrial and agricultural curves)

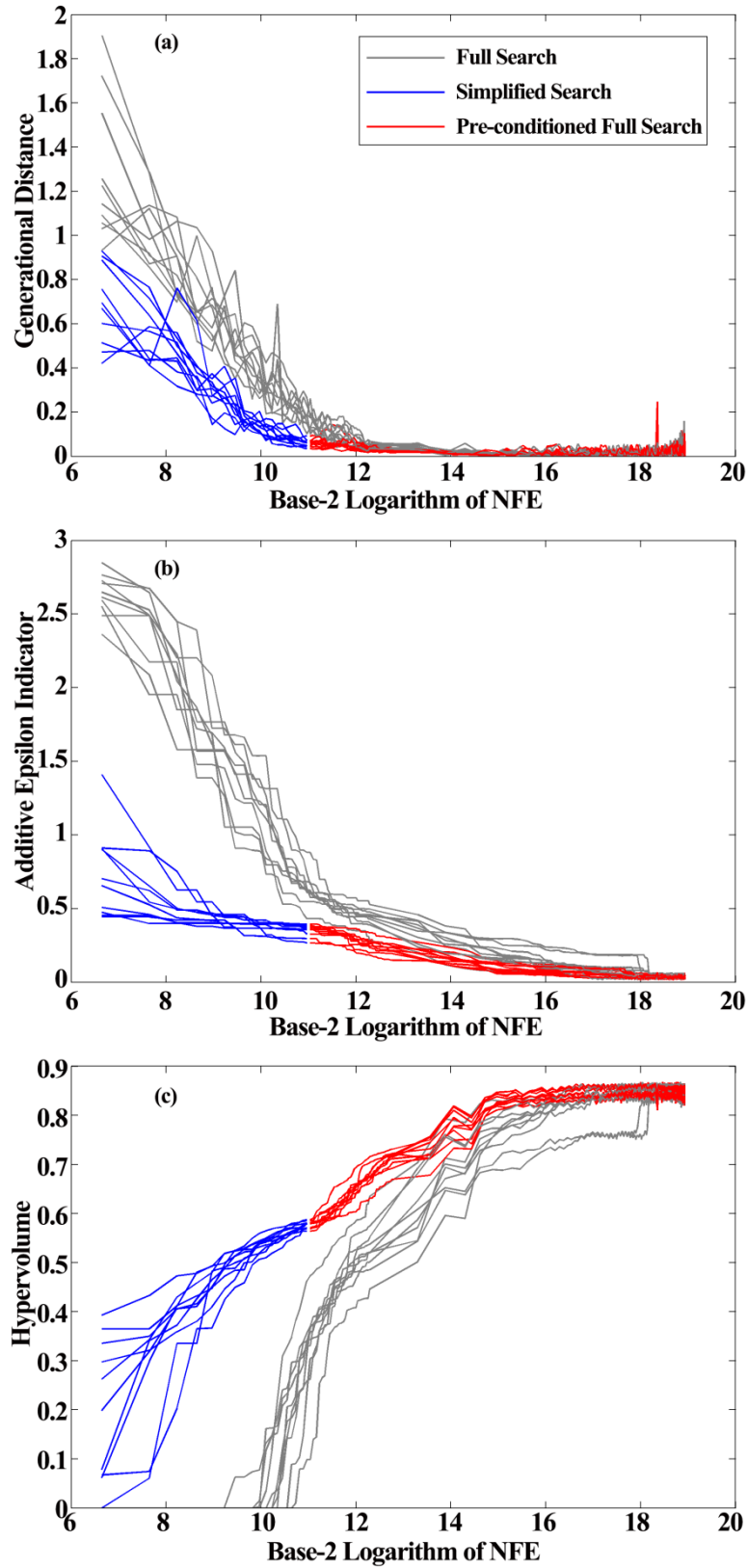


Fig. 5 Performance metrics for the Dahuofang ROS problem - (a) Generational Distance; (b) Additive Epsilon Indicator; (c) Hypervolume

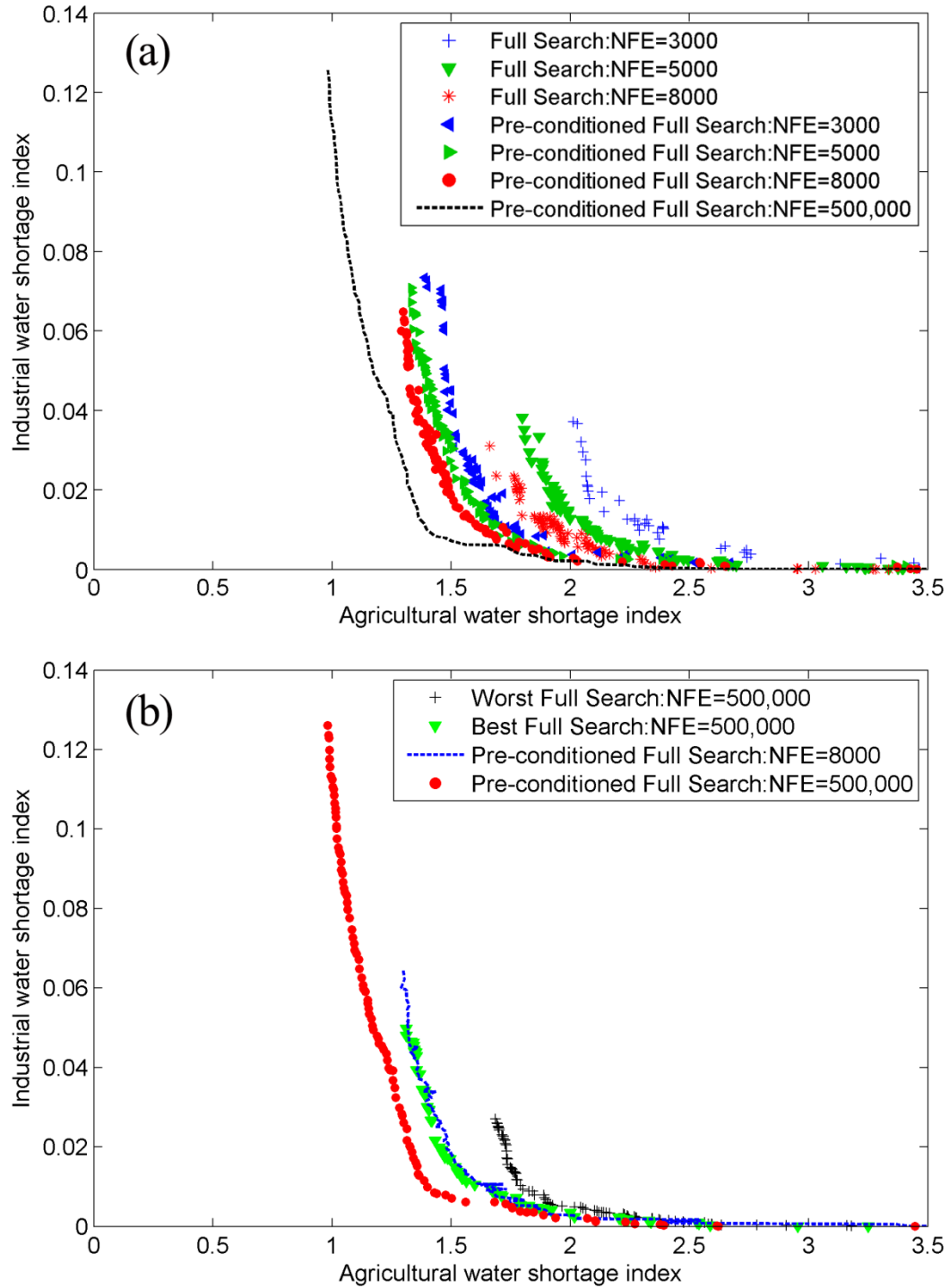


Fig. 6 Pareto fronts derived from pre-conditioned and standard full searches for the Dahufang ROS problem. (a) Sample Pareto fronts with different numbers of function evaluations for one random seed trial. (b) The best and worst Pareto fronts of ten seed trials.

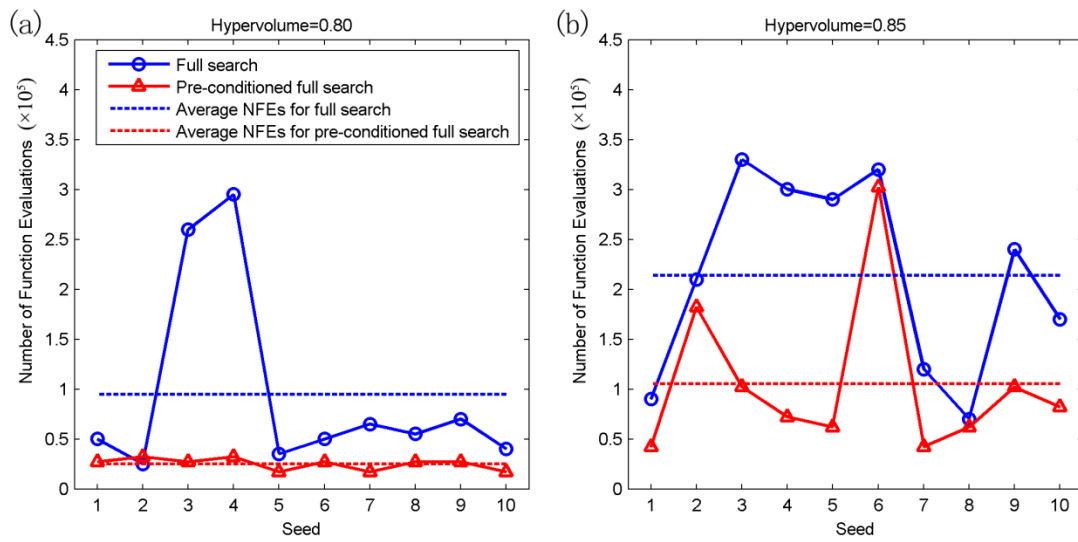


Fig. 7 Computational savings for two hypervolume values - (a) *hypervolume* = 0.80; (b) *hypervolume* = 0.85

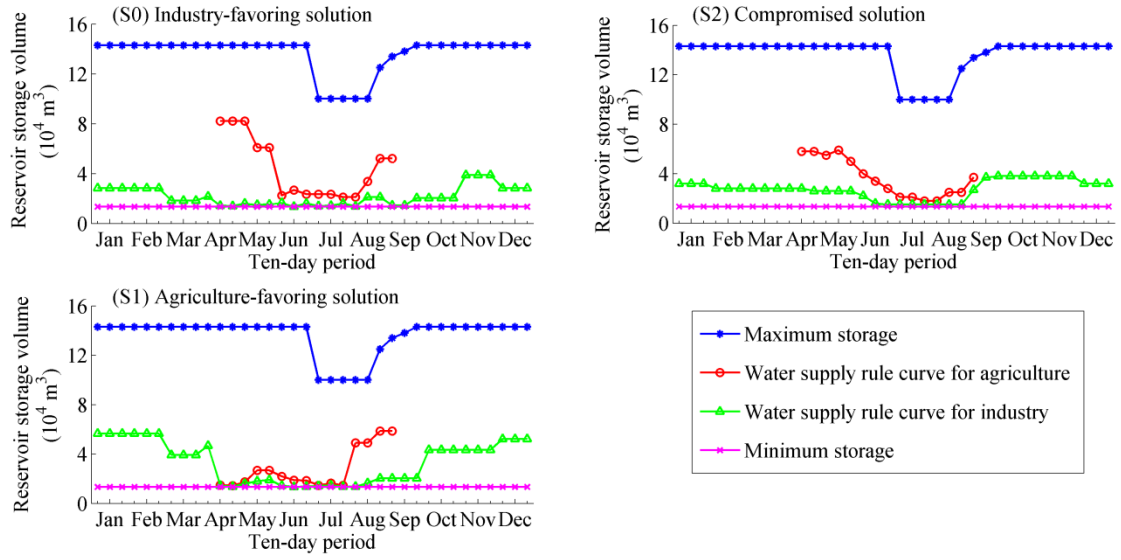


Fig. 8 Optimal rule curves for different solutions, (S0) Industry-favoring solution; (S1) Agriculture-favoring solution; (S2) Compromised solution

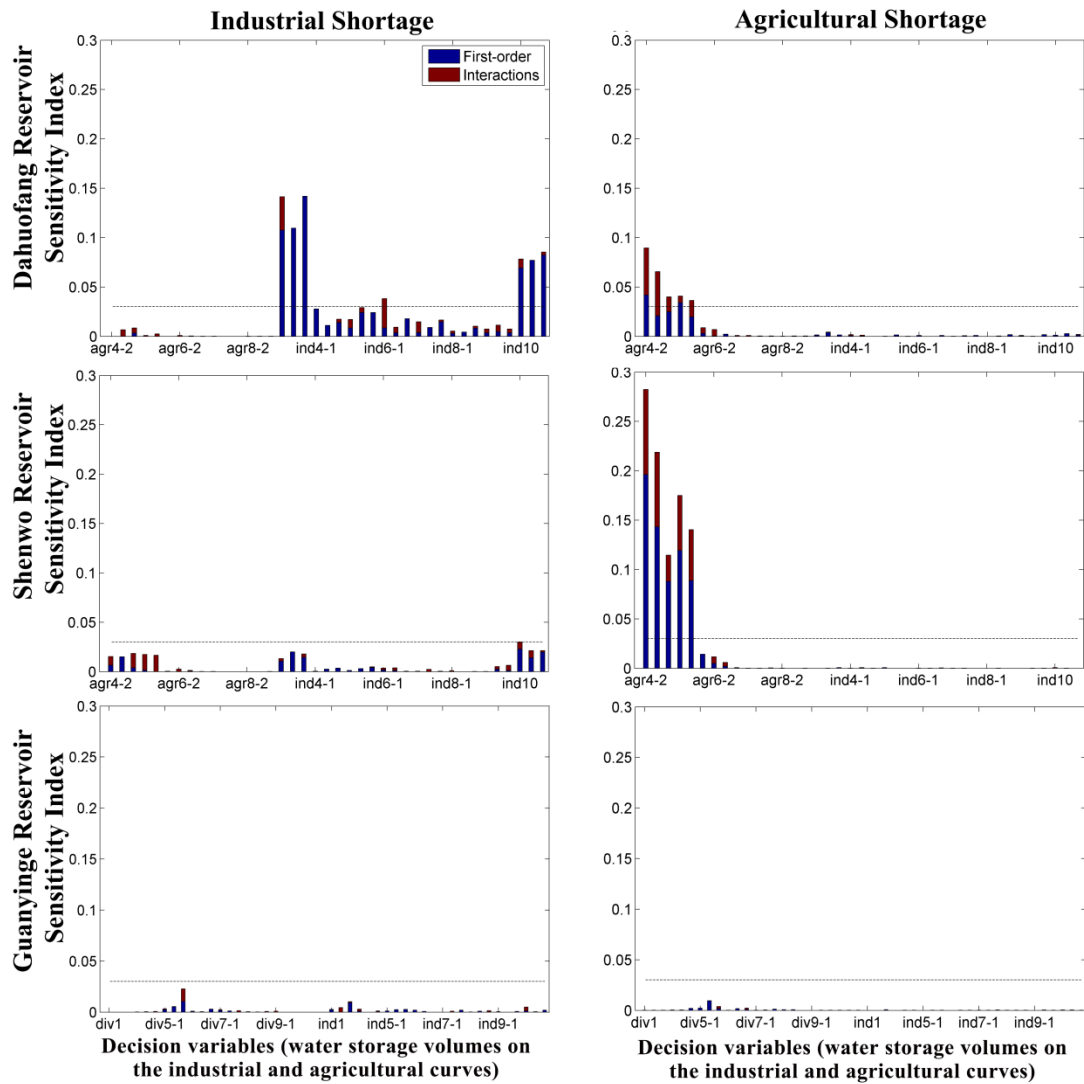


Fig. 9 First-order and total-order indices for the inter-basin multi-reservoir operation problem regarding industrial shortage index and agricultural shortage index. The x-axis labels represent decision variables (water storage volumes on the industrial, agricultural and water transferring curves)

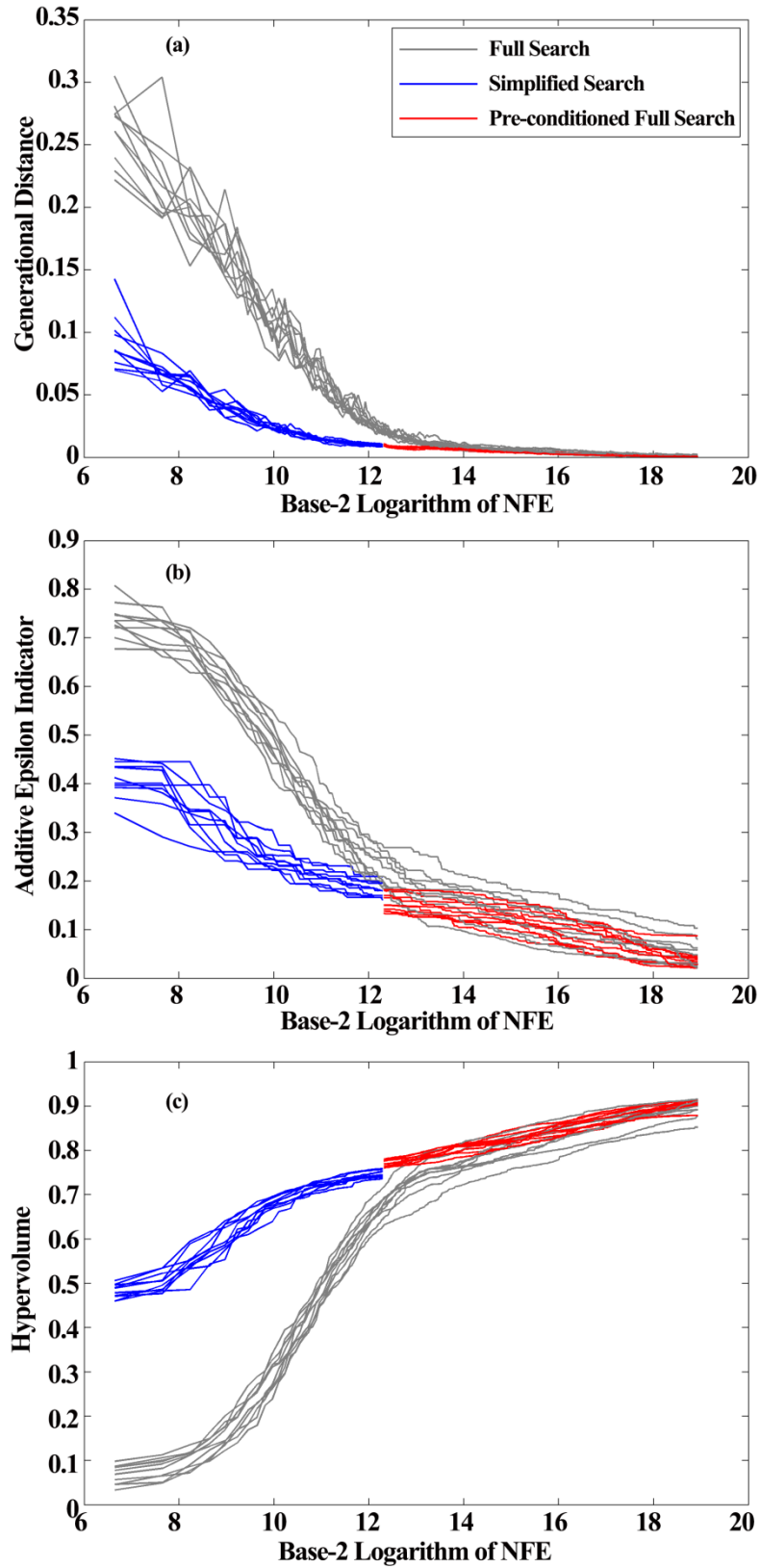


Fig. 10 Performance metrics for the inter-basin multi-reservoir water supply operation problem - (a) Generation Distance; (b) Additive Epsilon Indicator; (c) Hypervolume

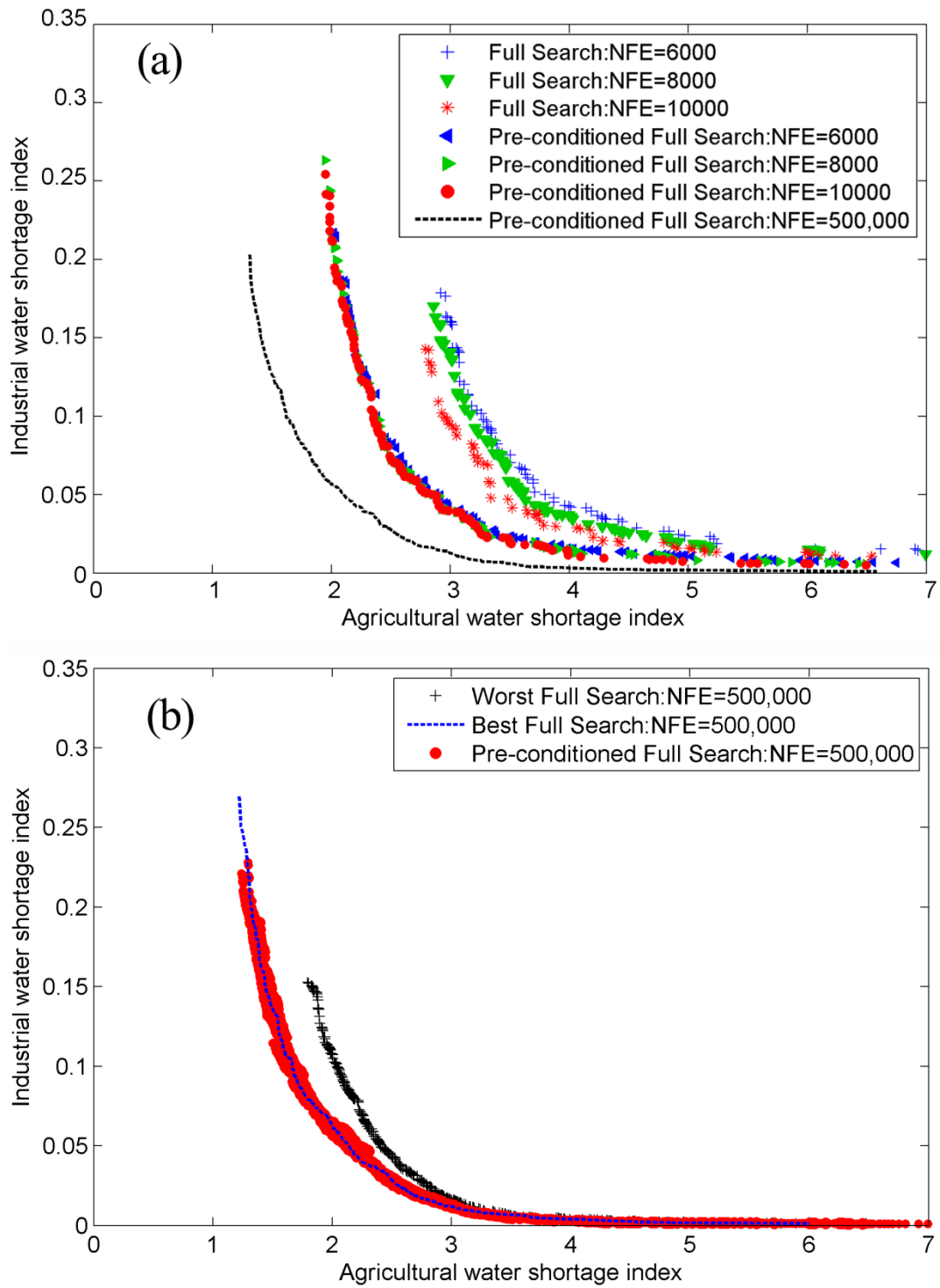


Fig. 11 Pareto fronts derived from pre-conditioned and standard full searches for the inter-basin multi-reservoir operation problem. (a) Sample Pareto fronts with different numbers of function evaluations for one random seed trial. (b) The best and worst Pareto fronts of ten seed trials.